Ozone induced plant injury on the Allegheny National Forest, 1998-2007
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Pollutants in the air can cause injury to forest plants, including trees. In sufficient concentrations, over extended time periods, air pollutants can cause declines in overall forest health and productivity. Acid deposition and ozone (0_3) are two air quality components of particular concern for northeastern forests. These two pollutants are discussed separately below, although it is their combined impact in an increasingly warming climate that poses the greatest threat to the health and stability of our national forests (Karnosky and others 2003).

Acid deposition involves the transfer of strong acids and acid forming substances (sulfur dioxide, nitrogen oxides, and ammonia) from the atmosphere to the Earth's surface (Driscoll and others 2001), where they cause acidification of forest soils and water, and adversely affect soil nutrient quality and vegetation nutrition. Documented changes in soil chemistry linked to acid deposition are considered important contributing factors in the decline of high-elevation red spruce and sugar maple trees in central and western Pennsylvania (Driscoll and others 2001, Horsley and others 2002). Although sulfur dioxide emissions that contribute to acid deposition have been noticeably declining in the Northeastern United States since 1994, nitrogen emissions have not changed, and have actually increased in some areas of the eastern United States, remaining relatively high in the Allegheny Plateau region. For this reason, acid deposition remains a concern and a variety of federal and state monitoring networks continue to track emissions and deposition patterns as researchers continue to look for evidence of ecosystem recovery from acid deposition. Forest health monitoring plots are used to detect plant stress and monitor changes in the health and condition of forest vegetation across the United States.

Like acid deposition, ozone is a regional pollutant subject to long-range transport from urban to rural areas making it difficult to contain or localize either the sources or the effects of this toxic air contaminant. Ozone is formed from the sunlight driven reactions of precursor pollutants, primarily nitrogen oxides (NOx) and volatile organic compounds (VOC's). Sources of NOx and VOC's (e.g., methane) include vehicle exhaust, emissions from industrial facilities, and solvent use (http://www.epa.gov/air/emissions/voc.htm.) During the summer months, increasing sunlight intensity and air temperature drive ozone formation, generating smog alerts in urban and rural areas. Damaging ozone episodes characterized by prolonged periods of high ozone concentration coincide with the growing season when plants are actively growing and most vulnerable to injury. Prolonged exposure to ozone is known to cause reductions in growth and biomass of eastern forest trees (Chappelka and Samuelson 1998), and has been shown to adversely affect ecosystem stability in the mixed conifer forest type of southern California (Miller and others 1996). More than 50 tree species have been identified as ozone-sensitive based on foliar injury symptoms, the most notable from eastern forests including eastern white pine, trembling aspen, black cherry, yellow poplar, and green and white ash (Karnosky and others 2007).

Ozone is the only regional gaseous air pollutant that has been measured at known phytotoxic levels at both remote and more urbanized forest locations across the United States. High ozone concentrations and injury are widespread in the eastern U.S., particularly in the mid-Atlantic region that includes Pennsylvania (Coulston and others 2003). Tree response to ozone is variable depending on a combination of environmental factors, plant properties, and ozone exposure characteristics that influence ozone uptake and injury. Soil moisture status is considered one of the most critical influencing factors because stomatal closure during periods of drought or low soil moisture content can severely limit gas exchange and, thereby prevent ozone uptake and therefore vegetation injury (Karnosky and others 2007).

Ozone causes visible, readily diagnosed foliar injury symptoms to certain ozone-sensitive tree species, woody shrubs and nonwoody herb species. We can use this visible injury response to detect and monitor ozone stress in the forest environment (Coulston and others 2003, Smith and others 2007). This approach is known as biomonitoring and the plant species used are known as bioindicators, or more specifically ozone detectors. Biomonitoring does not identify specific levels of ozone present in ambient air, but is used to determine whether conditions are favorable for ozone injury to occur and, through the formulation of a biosite index (BI), provides a way to quantify trends in ozone injury conditions (i.e., ozone stress) over time.

The Forest Inventory and Analysis (FIA) and Forest health Monitoring (FHM) programs of the U.S. Forest Service implemented a national ozone biomonitoring program in 1994 that currently includes over 1,200 biomonitoring field sites in 47 states. The Allegheny National Forest joined the program in 1998, implementing biomonitoring procedures on an enhanced sampling grid, and continued monitoring through 2007. Forest health and biomonitoring on the ANF follows national protocols, and personnel who collect monitoring data and biosite plant samples must attend national training and pass standardized exams. Plant injury data is evaluated and quantified by Gretchen Smith, FIA National Ozone Field Advisor (University of Massachusetts, Amherst, MA). This report summarizes the findings of the ANF biomonitoring program and reports by year the number of biosites evaluated and injured, the number of species and plants evaluated and injured, and annual fluctuations in ozone exposure, soil moisture, and foliar injury. Multi-year averages of the biosite index are used to report on the risk of probable ozone impact to the ANF forest resource. Comparisons are made between ANF and the biomonitoring results for PA and the Northeast region as appropriate. For detail on data collection methods, regional data summaries, analytical procedures, and additional resources on ozone and forest health, refer to Smith and others (2008).

The list of ozone-sensitive bioindicator plants on the ANF includes black cherry, pin cherry, blackberry, common milkweed, yellow poplar, spreading dogbane, white ash, and sassafras. Black cherry and blackberry were the most abundant species on the biomonitoring sites and sustained the most injury in terms of percent injured plants (Table 1). Pin cherry, milkweed and white ash were also injured occasionally while yellow poplar, spreading dogbane, and sassafras showed no visible injury response to ambient ozone concentrations. White ash and tulip poplar on the ANF tend to thrive on moister sites, so the lack on leaf injury is likely not due to moisture limitations. It is not known if the genotypes of these species on the ANF are atypical in their ozone sensitivity, or if the growing conditions (i.e., canopy closure) on the sites are limiting the downward movement of ozone to the sample tree canopy. Alternatively, it may be that ozone levels in the ANF are not consistently high enough to cause widespread plant injury.

Table 1- Number of plants evaluated for ozone injury on the ANF (1998-2007 FHM data; percent injured in parentheses)

Species	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Common milkweed (*Asclepias spp.*)	-	30 (0)	18 (0)	101 (8)	60 (0)	30 (0)	60 (2)	210 (1)	210 (0)	169 (0)
Back cherry (*Prunus serotina*)	60 (73)	232 (2)	128 (19)	167 (13)	150 (0)	180 (3)	210 (0)	330 (<1)	442 (0)	233 (2)
Blackberry (*Rubus allegheniensis*)	105 (58)	89 (41)	98 (57)	107 (21)	119 (22)	150 (4)	180 (3)	314 (<1)	450 (2)	240 (3)
Spreading dogbane	37 (0)	74 (0)	-	120	-	-	60 (0)	150	90 (0)	110

(*Apocynum androsaemifolium*)				(0)				(0)		(0)
White ash (*Fraxinus Americana*)	-	30 (0)	-	60 (5)	51 (0)	-	-	120 (1)	109 (4)	67 (6)
Sassafras (*Sassafras albidum*)	-	-	-	30 (0)	-	-	-	-	-	30 (0)
Yellow-poplar (*Liriodendron tulipifera*)	-	24 (0)	11 (0)	-	120 (0)	120 (0)	120 (0)	150 (0)	192 (0)	120 (0)
Pin cherry (*Prunus pensylvanica*)	11 (18)	31 (0)	30 (33)	75 (1)	90 (4)	60 (7)	120 (0)	180 (0)	338 (0)	150 (0)

Summarized biomonitoring data (all species combined) indicates that just over half of the sampled plants (50.2%) showed some symptoms of ozone injury in 1998, and just over a third (35.7%) were injured in 2000 (Table 2). In 1999, 2001, and 2002, less than 10% of the sampled plants were injured and thereafter (2003-2007) the percent injured dropped off to less than 3%. Regardless of the number of injured plants, the severity of injury for all years was generally low with most plants showing an average injury severity of less than 25%. Still, a very small percentage of plants in all years showed an average injury severity of greater than 50% , in some years greater than 75% (1998, 2000, 2002, 2007) suggesting a small population of very sensitive plants on the ANF.

Table 2- Percentage of sample plants showing ozone injury (1998-2007 FHM data)

Year	Number of sites evaluated	Number of plants sampled	Percent of sampled plants					
			No injury	1-6	7-25	26-50	51-75	>75
1998	4	213	50	14	20	8	6	3
1999	7	510	92	1	4	2	1	<1
2000	5	255	68	6	8	7	6	5
2001	6	660	92	2	3	2	1	0
2002	6	590	93	0	1	1	3	2
2003	6	540	97	2	1	<1	<1	0
2004	7	750	99	0	<1	<1	<1	0
2005	12	1,454	99	0	<1	<1	<1	0
2006	16	1,831	99	<1	<1	<1	<1	<1
2007	9	1,119	98	0	<1	<1	1	1

Coulston and others (2003) created an estimated surface of ozone risk for the Northeast using a 6-year rolling average of the BI values (1994-1999) that encompasses the early sampling years in the ANF (Figure 1). Results indicated that the Allegheny Plateau region had some of the highest ozone risk values in the Northeast and mid-Atlantic region, although the majority of the ANF fell into low to moderate risk category. A similar regional analysis of ozone risk was not available for this report. However, a national ozone risk map covering the 2002-2006 time period suggests that the risk of ozone injury to forests in Pennsylvania and the ANF is declining (Smith and others 2008). The site-level injury data presented in this report supports that contention, as both percent injured plants and BI values have dropped off significantly since 2002. In fact, the BI for the ANF has been less than 5 since 2003 (Figure 2), and would be mapped as no risk based on BI, if a similar mapping effort were completed again.

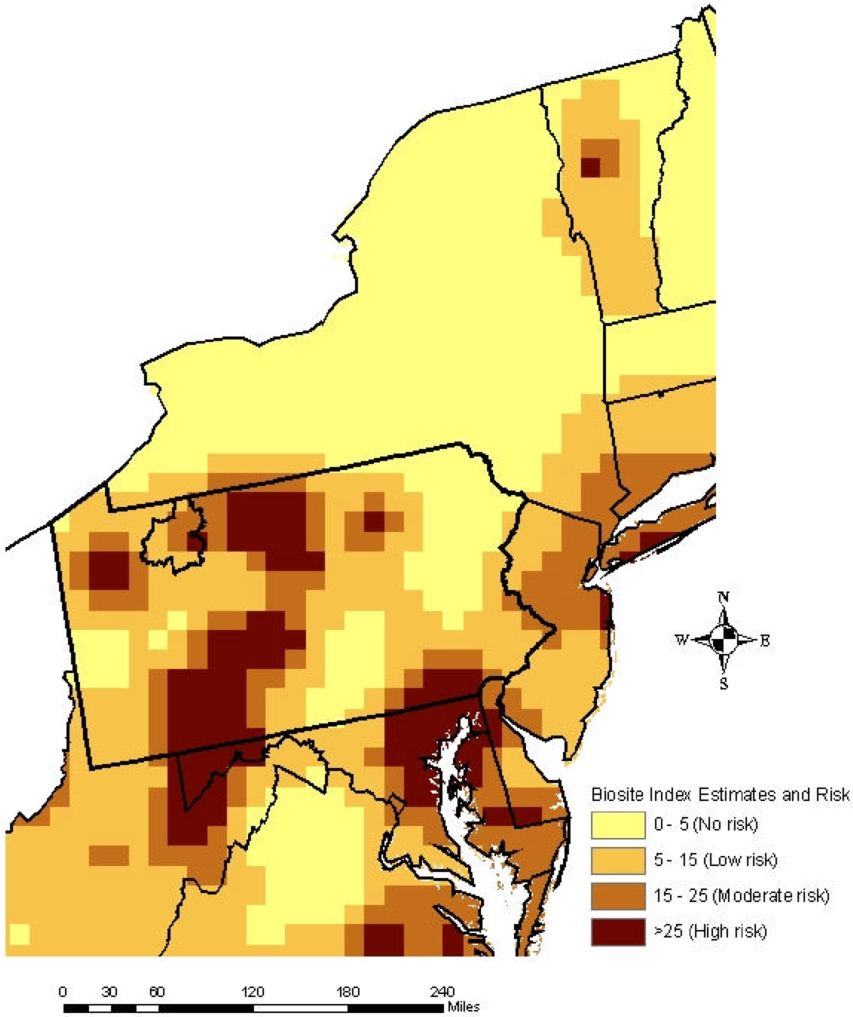
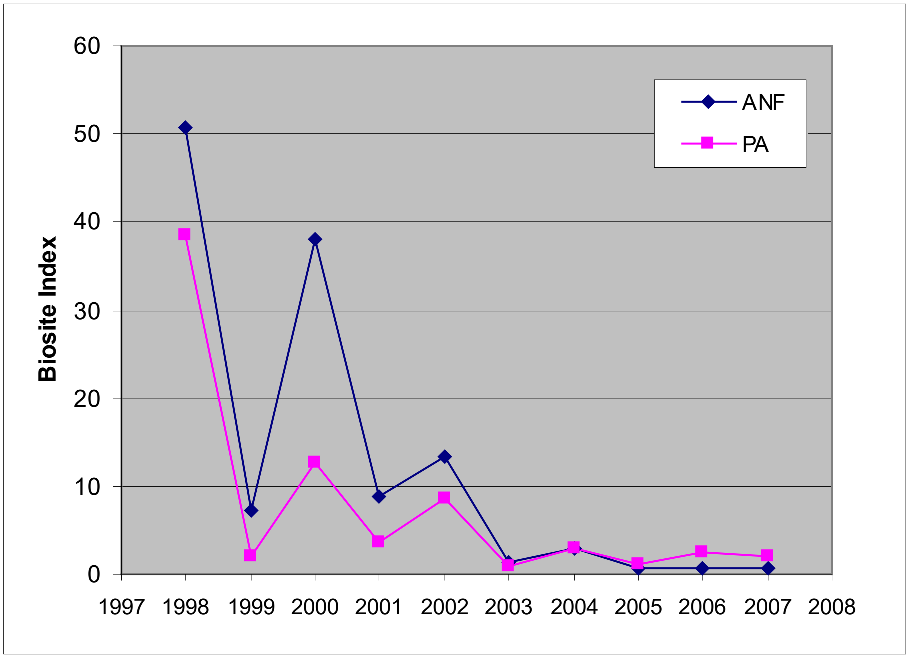


Figure 1- Estimates of ozone biosite index in the Northeastern United States (from Coulston eat al. 2003)

Trends in ozone injury conditions on the ANF from 1998-2007 as indicated by the BI data are similar to those for Pennsylvania as a whole (Figure 2 and Table 3). Biosite index values are highest in 1998, followed by a sharp drop in 1999, high values again in 2000, followed by a second drop in 2001 and relatively low BI values for the remaining years from 2002 through 2007. Generally, BI values in the ANF are higher than the BI values for Pennsylvania during the years with the highest injury scores (1998, 2000, 2002), and are more similar to the Pennsylvania data during the years with the lower injury scores. This is likely due to the fact that ozone injury conditions on the ANF are less variable than those for Pennsylvania as a whole thus increasing the consistency of response for any given year and generally magnifying the BI values in years when conditions are favorable for ozone injury.

Figure 2- Biosite Index for the ANF and Pennsylvania (1998-2007)



Injury Category	Biosite Index	Bioindicator response
1	0 – 4.9	Little or no injury
2	5.0 – 14.9	Light to moderate injury
3	15.0 – 24.9	Moderate to severe injury
4	>25	Severe foliar injury

Table 3 displays the number of biosites and plants evaluated and injured and percent injured plants for both the ANF and the State of Pennsylvania from 1998 through 2007. As with the BI data, the percent injured plants on both the ANF and the State of Pennsylvania significantly declined from 1998 to 2007. After 2002, the average percent injured plants on the ANF was very similar, or lower than percentages observed in Pennsylvania as a whole.

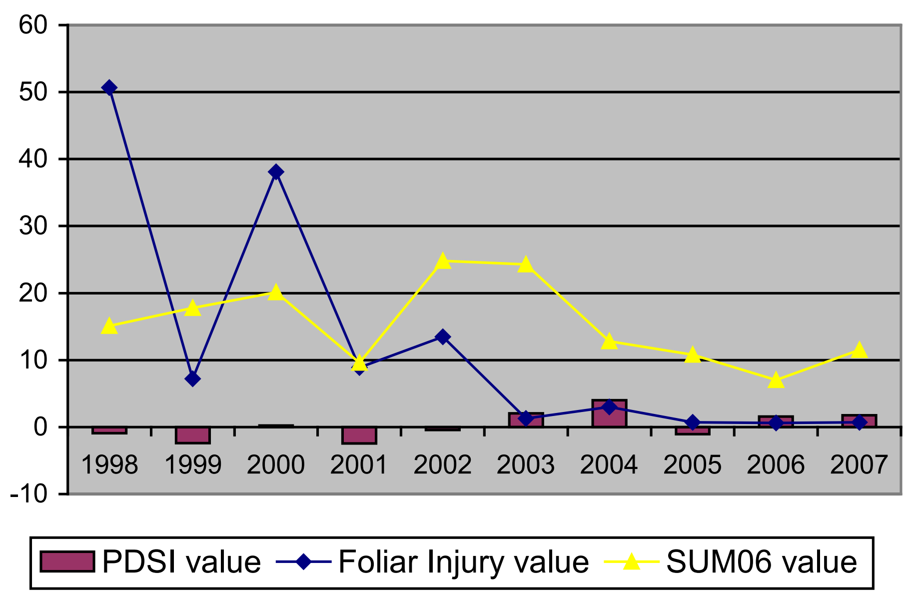
Table 3- Percent of sampled biosites and plants showing ozone injury (1998-2007)

Year	Number of biosites		Number of plants		Average
	Evaluated	Injured	Evaluated	Injured	Percent injured plants
Allegheny National Forest					
1998	4	4	213	107	36.9
1999	7	3	510	41	6.2
2000	5	3	255	91	16.6
2001	6	6	660	57	8.7
2002	6	3	590	29	5.3
2003	6	3	540	15	2.8
2004	7	5	750	6	0.9
2005	12	4	1,454	5	0.4
2006	16	7	1,831	16	0.7
2007	9	6	1,119	17	2.1

Pennsylvania (includes ANF)					
1998	100	52	2,299	652	25.2
1999	134	24	7,177	140	1.7
2000	100	63	7,402	778	10.7
2001	106	39	11,147	405	3.1
2002	49	32	5,548	439	7.7
2003	48	18	5,726	101	2.0
2004	49	19	5,303	195	4.4
2005	54	17	6,235	64	2.4
2006	58	30	5,763	118	2.7
2007	49	23	5,256	113	2.8

Although there appears to be an overall downward trend in ozone injury conditions over the 10 year sampling period (Figure 2), there are clearly annual fluctuations in the foliar injury data that need to be understood. An examination of the annual summary statistics for ozone exposure and soil moisture in relation to the BI data provides some explanation (Figure 3). Seasonal ozone exposures (SUM06 data) indicate that ozone concentrations varied between 10 and 20 ppb O_3 for 1998 to 2001, then rose above 20 ppb O_3 for 2002 and 2003 before dropping back down to the 10 ppb O_3 range for 2004 through 2007. Foliar injury values did not follow this same pattern. In 1999, for example, ozone concentrations were increasing, but foliar injury dropped sharply. This is explained by the drought moisture index (PDSI data) which indicates that drought conditions prevailed in 1999 in the ANF, closing the plant stomates, thus preventing ozone uptake and effectively reducing the foliar injury response of ozone-sensitive species. BI values were similarly reduced by drought in 2001, but rose in 2000 and again in 2002 as drought conditions lessened. Lower BI values in the remaining years after 2002 are likely due to the general decline in ozone exposures especially peak ozone values (>100 ppb O_3) that have dropped considerably since 2002 throughout the Northeast region (Smith 2009) and the country as a whole (U.S. EPA 2004).

Figure 3- Foliar Injury, PDSI, and SUM06 Values for ANF- 1998-2007



Summary:
Ozone is a regional pollutant subject to long-range transport from urban to rural areas, making it difficult to localize the effects of this air contaminant. Ozone causes visible, readily diagnosed foliar injury symptoms to certain ozone-sensitive tree species, woody shrubs, and nonwoody herbaceous species. This visible injury response on plants has been used as part of a national ozone biomonitoring program since 1994 in 47 states. It was used to detect and monitor ozone stress on the ANF between 1998 and 2007. From 1998 to 2007, there appears to be an overall downward trend in BI and ozone injury conditions (Figures 2 and 3). However, some ozone sensitive plants on the ANF are still showing symptoms of ozone-induced injury (Table 3). Additionally, there are annual fluctuations in the foliar injury data that need to be understood, and monitoring of ozone injury to plants should continue on the ANF. Additionally, some consideration should be given to initiating biomonitoring for other pollutants that may be present-specifically methane, hydrogen sulfide, and vehicle emissions. There is a need to investigate possible effects of ozone injury, including the overall health of trees, in areas identified as being high risk on the ANF in the past.

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